Chapter 2

REVIEW ON MONTE CARLO STUDIES IN
RADIOThERAPY

2.1 A brief history on previous studies

Monte Carlo Simulation techniques for particle transport studies were first introduced in 1940s for the design of nuclear weapons (Manhattan Project) by John Von Neumann, Stanislaw Ulam and Nicholas Metropolis, in the Los Alamos National Laboratory\(^9\). It was named after the Monte Carlo casino, a famous casino where Ulam's uncle often gambled away his money. It was then evolved into many different areas of applications, such as the much more peaceful applications in medical physics.

Historically, Monte Carlo (MC) Simulation techniques made a slow entry in the field of medical physics in the 1970s and early 1980s. Only very simple radiation geometries could then be modeled such as point sources irradiating homogeneous water phantoms. The limiting factors in those days were the low speed of computers and the limited flexibility of the few available MC codes. Even from the early days, MC methods provided a simple alternative to measurements to derive photon spectra from sources\(^{10,11}\).

Petty et al.\(^{12}\) in 1983 investigated the buildup doses from electron contamination of clinical photon beams using the EGS Monte Carlo simulation code. The contribution of contaminating electrons present in a clinical photon beam to the buildup dose in a polystyrene phantom was calculated and compared with measurements. Rogers et al.\(^{13}\) calculated the electron contamination in a telecobalt beam from an AECL therapy unit using EGS4 code. The study was limited to broad beam conditions and made several approximations to reduce the computing time.
In 1987, Han K et al. \textsuperscript{[14]} carried out the MC Simulation of an AECL Theratron 780 cobalt unit using Electron Gamma Shower computer code. The secondary collimators of intermeshing jaws were reduced to a continuous slab of lead to simplify the modeling. Their study showed that the observed increase in output of the cobalt-60 unit with increasing field size is caused by scattered photons from the adjustable collimator.

Udale in 1992\textsuperscript{[15]} studied the electron beam parameters for three Philips linear accelerators using EGS4 Monte Carlo code. Demarco et al. in 1994\textsuperscript{[16]} carried out the thick target Bremsstrahlung spectrum calculations to benchmark the Monte Carlo code MCNP against a set of precise measurements taken at the institute for National Measurements Standards in Canada. They validated the use of the Monte Carlo code MCNP4A for radiotherapy treatment planning applications. The integrated and mean energy of each bremsstrahlung spectrum were calculated for beryllium, aluminum and lead targets. They demonstrated that MCNP4A is capable of predicting the integrated bremsstrahlung yield within 6% accuracy with experimental results.

Comparison between two popular Monte Carlo codes EGS4 and MCNP while calculating the Percentage Depth Dose (PDD) data for radiotherapy beams was done by Love et al.\textsuperscript{[17]}. The geometry used for their simulations consisted of a conical photon beam impinging on a cylindrical water phantom of radius 28.21 cm. They used mono energetic source approximation for calculating the percentage depth dose for three radiotherapy beams with mean energy 1.25MeV, 1.9MeV and 3MeV to represent \textsuperscript{60}Co, 6MV, 10MV radiotherapy beams respectively. Their calculations agree with experimental results beyond build up region. They concluded that EGS code is at least 50% faster than MCNP code for radiotherapy dosimetric calculations.
Felix C et al. in 1998\textsuperscript{[18]} published an article about forward and adjoint methods for radiotherapy planning. Their aim was to study the feasibility of sensitivity theory developed for nuclear applications to radiotherapy treatment planning and implemented forward and adjoint mathematical approaches to calculate the sensitivities of dose distributions in a mathematical phantom. The potential efficiency and strength of forwarded and adjoint methods of dose calculations using the Monte Carlo code MCNP were demonstrated in their work. They concluded that, the sensitivity of dose with position, angular distribution intensity and spectra of radiation source could be calculated efficiently with Monte Carlo Methods and argued that better optimization of radiotherapy planning is possible with Monte Carlo Methods rather than using trial and error methods.

A detailed and realistic modeling of the treatment head of Eldorado 6 telecobalt machine was done by Mora et al. in 1999\textsuperscript{[19]} using BEAM-EGS4 code. They simulated the collimation system using a simplified model consisting of solid blocks of lead. Their study included the modeling of source, source housing, primary collimator and adjustable leaf collimator assembly. Their study shows that the variation of air kerma output with field size is almost entirely due to collimator scatter and not related to the shadowing of primary photons as would happen in accelerators. In order to reduce the large computing time they split the simulation in to three steps. In the first step cobalt source, lead housing and primary collimator were included. The phase space file data for the particles reaching the scoring plane before the outer collimator was stored and used for the next part of simulation as the input source. The second part includes the passage of the particle through the adjustable collimator and the air medium above the surface plane of the phantom. In the third step the phase space files for different field sizes
were reused as an input file for dose calculations. In order to improve the efficiency they used different cut off energies for particle transport. They used some of the variance reduction techniques such as range rejection of electrons to improve the efficiency of calculation. The basic method used in the simulation of Eldorado6 telecobalt by Mora et al. was thereafter followed by several authors for the simulation of different telecobalt machines. In the year 2009 B Muir et al.\[20\] carried out a review study of the simulation inputs of Eldorado 6 done by Mora et al. The authors concluded that the input files for the $^{60}\text{Co}$ unit used in BEAM simulations with EGS4 by Mora et al are still valid for simulations of BEAMnrc using EGSnrc code. In the present study we are also following a similar approach as suggested by Mora et al for the simulation of telecobalt machine.

The experimental verification of Monte Carlo based calculations were done by Lu Wang et al. in 1999\[21\] by using various homogeneous phantoms. The phantom geometries included in their studies were simple layered slabs, a simulated bone column, a simulated missing layer hemisphere and an Anderson anthropomorphic phantom. They used EGS4 Monte Carlo code for their work. They validated the accuracy of Monte Carlo methods for clinical applications and concluded that long computing time is required to achieve reasonable accuracy. Monte Carlo methods can be used as benchmark against other dose calculation methods and can be used to replace measurements when the measurement is difficult to carry out. They pointed out that to implement Monte Carlo Method for routine treatment planning more and more studies required.

A Monte Carlo based model of a linear accelerator beam using MCNP code was developed by Lewis et al.\[22\] in 1999. They used the model initially to generate the energy distribution and angular distribution of the X-ray beam for the Philips linear accelerator in a plane beneath the
flattening filter. The data was subsequently used as a source of X-ray at the target positions. They concluded that the technique may be used to calculate energy spectra of any linear accelerator with acceptable results in a reasonable run time.

Using BEAM MC code system Sheik et al. in 2000\cite{23} compared the measured and Monte Carlo simulated dose distributions from the NRC LINAC. A detailed geometry of the LINAC was included in their simulation. They used two energies 10 and 20 MV for simulation and found that the calculated and measured PDD values for both energies are in good agreement (within 1%). However the calculated and measured values showed some discrepancies in the buildup regions. They have taken a great effort to understand the factors influencing the penumbral shape of the LINAC beam. They concluded that the knowledge of exact geometry of collimators is necessary to correlate measured and simulated behavior in the penumbral region and in general BEAM code is capable of very accurately simulating the photon beams from medical LINACs but the accuracy depends on accurate information about both the accelerator head and incident electron beam.

The applications of Monte Carlo techniques for primary standards of ionizing radiation and dosimetric protocols were reviewed by Rogers\cite{24} using Monte Carlo methods. Nutbrown et al. in 2002\cite{25} evaluated conversion factors for the absorbed dose in graphite to water for high energy photon beams. A complete simulation of the treatment head of a Theratron 780C telecobalt machine was done by Teimouri et al.\cite{26} in 2004 using MCNP code. They have compared the PDD values obtained from simulation to the values published in BJR Supplement 25 and found a good agreement between the published and calculated data. In their study instead of phase space file method they utilized a single simulation method to reduce the systemic error.
The use of Monte Carlo methods for routine clinical treatment planning was presented by Rogers and Mohan\cite{27}. As per their argument even though Monte Carlo techniques represent the ultimate answer to the problem of accurate dose calculation the speed of calculation is still the issue. An accurate specification or the modeling of the clinical beam (including patient specific shaping devices) is essential for the overall calculation to be more accurate. They concluded that implementation of Monte Carlo code for routine clinical treatment planning require the development of various standard tools for comparing various approaches and for assessing the speed of the calculation in a meaningful way.

Characterization of Gammatron1 tele-cobalt unit at a secondary standard dosimetry laboratory was done by Asa Carlsson et al.\cite{28} in 2010. Their study shows that the change in $K_{air}/D_w$ after source exchange was due to the difference in spectral distribution of sources with different source designs. In 2010 Ayyangar et al.\cite{29} modeled Phoenix telecobalt machine head using BEAMnrc code. Their aim was to design a practical multi-leaf collimator (MLC) system for the cobalt therapy machine and to check its radiation properties using the Monte Carlo method. Comparison with standard depth dose data tables and theoretically modeled beam showed good agreement within 2%. They have concluded that, it is possible to generate accurate data for treatment planning purposes using the MC approach and the MC simulation has proved helpful to evaluate MLC design for cobalt-60 teletherapy machine. They have also concluded that without use of MC simulation it was not possible to assess the radiation properties of the MLC design especially near beam edges where critical structures could lie. In 2011 Jar Won Shin et al.\cite{30} simulated a typical teletherapy unit with GEANT4 MC Simulation code. They have obtained the energy spectra, PDD, Peak Scatter Factor and Tissue Air Ratio parameters for the telecobalt machine from the
simulation. They have concluded that the results are within 1% errors in comparison with MCNP and EGS simulated results.

2.2 Evolution of different Monte Carlo transport codes

There were various earlier codes as discussed by Bielajew et al.\textsuperscript{[31]} developed to model coupled electron photon transport. However, the basis of all the current transport codes is a book chapter written by Berger\textsuperscript{[32]} in 1963 in which he outlined the condensed history technique of electron transport. Berger with Steve Seltzer\textsuperscript{[33]} developed the ETRAN code which has become the basis of the electron transport algorithm for several general purpose codes. The ETRAN Monte Carlo model, an acronym for electron-transport was originally developed at the National Bureau of Standards, USA, to simulate the transport of electrons and photons involving energies up to a few MeV, being extended later on for calculations at higher energies. The extension of the ETRAN-based Integrated Tiger Series (ITS) system of codes to the multi-GeV region, was developed there after by Miller in 1989\textsuperscript{[34]}. ETRAN is a Class I code, which emphasizes the physics of electron transport, its main characteristics being the accurate treatment of electron multiple scattering and bremsstrahlung interactions including cross sections differential in energy and angle. To take into account low-energy transport, ETRAN includes characteristic X-rays from the K-shell and auger electrons after the emission of a photoelectron, but neglects coherent scattering and binding corrections to incoherent scattering which have been included in an updated version of the ITS system\textsuperscript{[35]}.

The ETRAN code provides sophisticated electron transport techniques but include only the simple geometries such as infinite media or plane-parallel slabs of different materials\textsuperscript{[36]}. The family of ITS code which are based on the ETRAN system provides geometrical packages of increasing complexity\textsuperscript{[37]}. ITS consists of three main codes, TIGER,
CYLTRAN and ACCEPT, which allow the user to simulate electron and photon transport down to 1keV in plane-parallel slabs, cylindrical geometry or any combination of the geometrical bodies included in its default combinatorial package, respectively. The ITS system also consists of special versions of these three codes (called ‘P-codes’) which include ionization of all shells and atomic relaxation from the K, L, M and N shells.

During the 1970s a number of specialized Monte Carlo codes were written for application to radiotherapy physics like the codes developed by Patau and Nahum in 1976[^38], which were developed on mainframe computer systems and mainly for electron transport. There after the availability of minicomputers in many medical institutions made possible the development of ‘smaller’ Monte Carlo codes capable of simulating either specific problems in radiotherapy physics with photon beams[^39,40], the transport of photons in Compton-scatter tissue densitometry[^41]or the full electromagnetic cascade used to derive quantities for electron dosimetry in water[^42,43].

The EGS (Electron Gamma Shower) Monte Carlo system was originally developed at Stanford Linear Accelerator Centre (SLAC) to simulate high-energy electromagnetic cascades. The SHOWER code which was the "seed" for the EGS computer program was brought to SLAC around 1965 by Hans-Hellmut Nagel of Bonn University. Nagel's program was created for use in designing elements of accelerator machinery such as beam stoppers, collimators etc during construction of the Two-Mile Accelerator and beam lines at SLAC. However, Nagel's code was too specific to solve other problems in high-energy physics. Two physicists of SLAC W Ralph Nelson and Richard Ford took the task of rewriting the code to achieve the necessary generalization. Their combined efforts produced the first version of EGS in 1978[^44]. EGS is a
Class II code\cite{35} where the production of knock-on electrons and bremsstrahlung are treated individually. As a consequence, one of the requirements to run the system is to define threshold energies for such events and pre compute data (using the code PEGS) for each threshold, which in general will vary for different types of calculation. The EGS, which was well documented, user-friendly, versatile and supported by technical experts, was offered free of charge to the scientific community. The program soon became very popular and developed by a large user community. The new enhanced version of EGS developed by NRCC (National research centre Canada) is EGSnrc, which is being used in our research work.

Even though in medical physics EGSnrc remains the most widely used general purpose Monte Carlo radiation transport package, a variety of other code systems are also available. The PENEOPE code has a detailed treatment of cross sections for low-energy transport and a flexible geometry package which allows simulation of accelerator beams\cite{45,46,47}. The MCNP system\cite{48} is maintained by a large group at Los Alamos National Laboratory and has many applications outside medical physics because it was originally a neutron–photon transport code used for reactor calculations. This code has a very powerful geometry package and has incorporated the ETRAN code system’s physics for doing electron transport. The GEANT4\cite{49} is a general purpose code developed for particle physics applications. It can simulate the transport of many particle types (neutrons, protons, pions, etc). GEANT4 has been used for various application in radiotherapy physics\cite{50,51} and is the basis of the GATE simulation toolkit for nuclear medicine applications in PET and SPECT\cite{52}. GEANT4 still demonstrates some problems when electron transport is involved and runs considerably slower than EGSnrc in these applications\cite{53} but the overall system is very powerful.